Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 61 (2014) 695 – 699

Energy Procedia

Semi-Dynamic Simulation of ORC Based Diesel Engine WHR System

Guohong Tian [a,b] *, Yong Zhang [b], Tony Roskilly [a]

[a]Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
[b]Chongqing University of Technology, Chongqing, 400054, China

Abstract

Organic Rankine Cycle (ORC) based engine waste heat recovery (WHR) has been recognised as a promising technology as it can potentially improve the total engine efficiency significantly and has no noticeable effect on engine operation. In this paper, a model based investigation in this technology has been presented. A semi-dynamic model has been developed which consists of a detailed 1-D engine acoustic model, an ideal ORC thermodynamic model and a bridging model that couples the two sub-models and enables a dynamic data transfer between these two models, thus enables a semi-dynamic simulation. A parametric analysis has been carried out for working fluid selection that allows the best match of the engine working conditions. Water, R134a and R245fa were selected as working fluid candidates, and the simulation results suggest that despite water has the highest cycle efficiency, it is unsuitable to use it because as a wet fluid, water cannot be heated to superheated steam in most of the conditions. For the two organic refrigerants, R245fa is superior to R123a in terms of cycle efficiency. A cyclic simulation following a WHSC engine operation cycle suggests that the control of working fluid flow rate is necessary to maintain a high ORC cycle efficiency. A preliminary optimal control can achieve 8.1% fuel economy improvement throughout the whole cycle.

Peer-review under responsibility of the Organizing Committee of ICAE2014

Keywords:Waste energy recovery; organic rankine cycle; dynamic model

1. Introduction

Organic Rankine Cycle (ORC) based Waste Heat Recovery (WHR) technology recently has attracted a lot of attention due to the climbing energy price and increasing requirement of reducing carbon emissions [1]. Using organic fluids as the working media, ORC can generate power utilising low grade heat which is otherwise dispersed into environment and wasted. The applications of ORC include geothermal, low grade waste heat from process industry, solar, etc. [2].

The investigation of utilising ORC in vehicle engines is relatively new mainly due to the high complexity and the restrict requirement of cost control [3, 4]. Usually over 60% of the energy generated by fuel combustion is dispersed through coolant and exhaust [5]. Having been developed over a century, it is extremely difficult to make a breakthrough in internal combustion (IC) engine technologies to

* Corresponding author. Tel.: +44(0)191 208 3902;
E-mail address: guohong.tian@ncl.ac.uk.

Peer-review under responsibility of the Organizing Committee of ICAE2014
doi:10.1016/j.egypro.2014.11.945

substantially improve fuel efficiency. However targeting the heat in coolant and exhaust gas, WHR could offer a potential to improve the total efficiency of the vehicle powertrain for over 10%. Compared to other WHR technologies, ORC has the advantages of relatively low cost, high efficiency and no noticeable effect on engine operation. However compared to passive WHR systems such as thermo-electric panel which direct generates electricity by thermo-electric effect [6], ORC requires active control of the cycle to maintain an optimal operation condition, which is determined by the engine working conditions, therefore needs more detailed investigation, particularly in conjunction with the engine operations.

In this paper, we present a numerical investigation in ORC diesel engine WHR system by a semi-dynamic model. This model consists of a number of sub-models which are dynamically coupled thus allows data to be transferred between the sub-models in a dynamic manner. The purpose of developing this model is to investigate the interaction of engine operation and ORC operation. Since the ORC model is an ideal Rankine cycle model, the system model is not fully dynamic. But it is capable of running an engine operation cycle and proposing a preliminary optimal control strategy.

2. Model Description

The schematic diagram of the engine WHR system model is shown in Figure 1. It is comprised of a number of models: a detailed 1-D acoustic engine model built in WAVE and an ideal Rankine cycle model built in Engineering Equation Solver (EES). The WAVE engine model includes all the engine specifications, such as combustion chamber geometry, inlet and exhaust valve, inlet and outlet pipes, turbo-charger, silencer, air filter, and injection specifications. It is capable of simulating engine performance and emissions to a high accuracy (within average uncertainty of ±5% compared to testing results) and is widely used in engine industry. The engine selected in this work is a 4 cylinder direct injection Deutz diesel engine with specifications listed in Table A1. The engine WAVE model has been validated against the manufacturer data sheet to provide confidence for the WHR simulation.

The engine exhaust gas is used as the heat source to drive the ORC. A bridging model was built in Simulink to dynamically communicate with the WAVE engine model and read the exhaust gas parameters including components, flow rate and temperature. 4 components were considered, which were O2, CO2, N2 and H2O, and the rest were neglected due to the small amounts. From these parameters, the enthalpy contained in the exhaust gas can be calculated. This Simulink model can also dynamically communicate with ORC model which can transfer the exhaust gas information for heat exchanger calculation.

The ORC model is a basic 4 components Rankine cycle model built in EES. The components include an isobaric boiler, an isobaric condenser, an expander with fixed isentropic efficiency of 80%, and a pump with fixed isentropic efficiency of 90%. The two exchangers (boiler and condenser) are assumed as counter-flow type. The boiler was modelled by ε-NTU method and has a fixed UA value of 50W/K in order to ensure a sufficient heat exchange area at the high engine load area, and avoid reducing the exhaust gas temperature below 150°C which will cause vapor condensing and consequently exhaust pipe rusting. In the simulation process, the boiler was considered as three sections and is schematically illustrated in Figure 2. The working fluid is considered to be heated to boiling temperature in section 1, heated to saturated gas (2 phase heating) at the end of section 2, and superheated in section 3. In the simulation process, if the sum of UA values of section 1 and 2 is greater than 50W/K which is the total boiler UA value, the working fluid is considered to be heated to wet vapour (or saturated if equals to 50W/K). The working fluid and exhaust gas properties are from the EES library. In the 2 phase heating section, the heat capacity of the working fluid is considered as infinite (1000 times of the gas heat capacity in actual programming).

In the ORC modelling, the temperature at state 1 (see Figure 1) is set to 50°C and the quality is set to x_1=0 (saturated liquid). The flow resistance inside the heat exchangers and pipes is neglected.

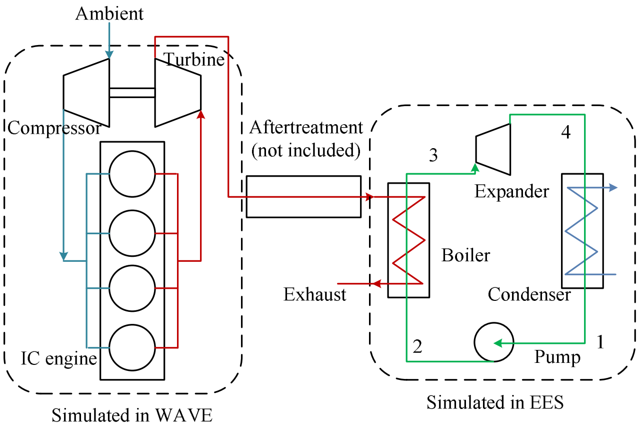

Fig. 1. Schematic engine WHR system

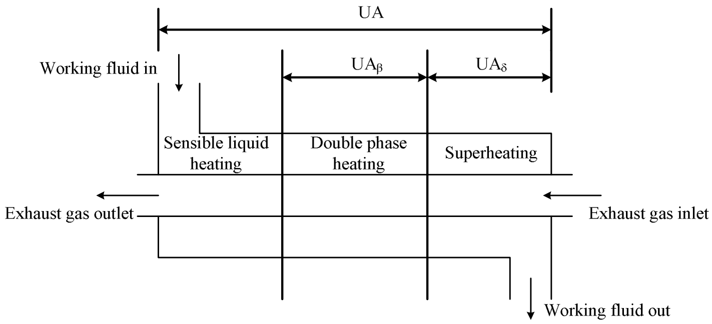

Fig. 2. Schematic boiler heat exchanger model

The ORC cyclic power is defined as $P_{ORC} = P_{expander} - P_{pump}$. The total efficiency is calculated by $\eta_{tot} = (P_{engine} + P_{ORC})/\dot{m}_{fuel}H_v$, where P_{engine} is the engine power, $\dot{m}_{fuel}$ is the fuel flow rate, and H_v is the lower heating value of diesel. The total system efficiency improvement is then defined as $\text{Improvement}(\%) = (\eta_{tot} - \eta_{engine})/\eta_{engine} \times 100\%$, where η_{engine} is the engine efficiency.

3. Results and Discussion

3.1 Working fluid selection

Three working fluid candidates, including water, R134a and R245fa have been investigated to find the best suitable working fluid for this application. The selection of the candidates represents 3 types of working fluid, which are wet (water), isentropic (R134a) and dry (R245fa) fluids. The selection of the candidates also meets the requirement suggested by previous researchers, which are: a. Chemical stability at operating temperatures and pressures; b. Non-toxicity and compatibility with materials; c. Low flammability; and d. Environmental friendliness [7].

When using different working fluid, the ORC operation parameters need to be adjusted accordingly. When condensing temperature is set at 50°C, the condensing pressure for water, R134a and R245fa are 12.34kPa, 1319kPa and 343.2kPa, respectively. When water was selected, considering the exhaust gas temperature range and the requirement of superheating the fluid to avoid condense occurring in expander, the boiling pressure was set at 1000kPa, and mass flow rate was set at 0.006kg/s after preliminary optimisation based on the enthalpy contained in the exhaust gas. For the same reason, when R134a was

used, the boiling pressure was set at 4000kPa, and mass flow rate was set at 0.08kg/s. When R245fa was used, the boiling pressure was set at 2000kPa, and mass flow rate was set at 0.05kg/s. During the simulation, engine speed was fixed at 1500rpm, and engine load was swept from 20% to full load. The expander power output, efficiency improvement and quality at the boiler outlet are shown in figure 3.

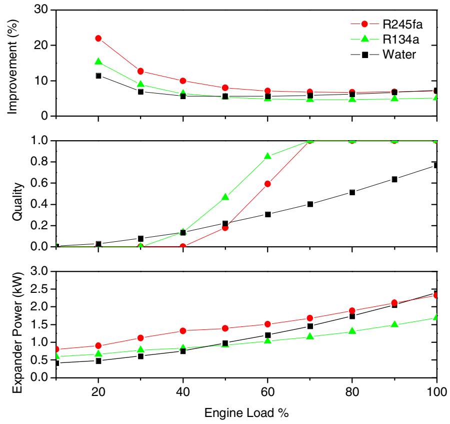

Fig. 3. WHR system performance for different working fluid candidates

It can be clearly seen, when the mass flow rate was set to achieve a better cyclic efficiency, over 2 kW power output from the ORC can be achieved at full engine load, when water and R245fa were used, which improved the total efficiency by 7%. When R134a was used, the highest power output was 1.7kW at full engine load, which contributes to a 5% efficiency improvement. When water was used as working fluid, with this mass flow rate, the output at the boiler outlet was always wet vapour despite the engine load, which will introduce significant issues for expander design and maintenance. When the other two organic fluids were used, with these mass flow rates, the output at boiler outlet were saturated or superheated vapour when engine load was over 70%. Since they are either isentropic or dry fluids, the expander will be able to function properly. Therefore when water is selected, mass flow rate will have to be reduced to achieve superheated vapour at the boiler outlet, which will reduce the power output and the system total efficiency. When the other organic fluids are used, the mass flow rate will need to be adjusted according to engine operation condition to ensure the fluid has proper condition when enters the expander. Comparing the 3 candidates, and taking the engine exhaust gas temperature range into consideration, water is not a suitable working fluid in this application despite the high power output, and R245fa is superior to R134a in terms of efficiency improvement and pressure requirement, therefore is chosen for following dynamic engine cycle simulation.

3.2 Engine cyclic simulation

The novelty of the model introduced in this paper is that by dynamically linking the 3 sub-models, it is capable of conducting a dynamic simulation of engine WHR and investigating the impact of engine working on WHR system operation, because usually IC engine runs in a highly dynamic manner, particularly for on-road vehicle powertrains. This nature of the dynamic working condition of engines determines that the WHR system needs to be controlled carefully in order to achieve the best performance and avoid any damage towards components, particularly the expander. In this paper, World Harmonised Stationary Cycle (WHSC) was chosen as the engine working cycle, only R245fa was selected as the fluid. The WHR system performance is illustrated in Figure 4 with controlled R245fa mass flow rate. The boiler outlet can be maintained at the most time as saturated vapour when mass flow rate is controlled. The system total efficiency improvement over the whole cycle was 8.1%.

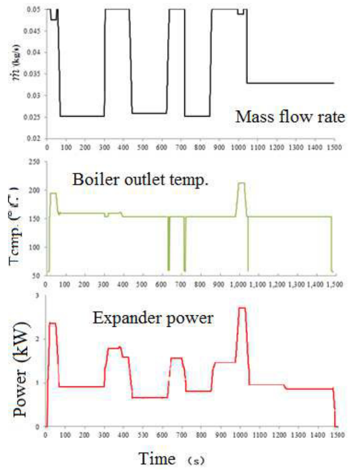

Fig. 4. WHSC cycle WHR system performance

4. Conclusions

This paper introduced a semi-dynamic model for ORC based engine WHR system simulation. 3 sub-models were developed to carry out the numerical simulation which allows dynamic data communication among them. This work can be concluded as:

- For the 3 candidates investigated, water is not suitable for this application, and R245fa has better performance than R134a due to the higher power output and lower pressure requirement;
- The ORC needs to be controlled according to engine working conditions;
- With preliminary optimisation, the total efficiency improvement over a WHSC cycle was 8.1% when R245fa is used.

It is worth mentioning the ORC model is static and needs to be improved to dynamic model in the future in order to carry out a fully dynamic model simulation.

Acknowledgements

The authors acknowledge the support of this work from the Chongqing Municipal Commission of Education (KJ120823).

References

[1] T. Wang, Y. Zhang, Z. Peng, G. Shu, A review of researches on thermal exhaust heat recovery with Rankine cycle, Renewable and Sustainable Energy Reviews, 15 (2011): 2862-2871

[2] Chen, H., D.Y. Goswami, and E.K. Stefanakos, A review of thermodynamic cycles and working fluids for the conversion of low-grade heat. Renewable and Sustainable Energy Reviews, 2010. 14(9): p. 3059-3067.

[3] Iacopo Vaja, A.G., Internal Combustion Engine (ICE) bottoming with Organic Rankine Cycles (ORCs) Energy, 2010. 35: p. 1084-1093.

[4] T. Endo, S.K., Y. Kojima, K. Takahashi, T. Baba, S. Ibaraki, T. Takahashi, M. Shinohara, Study on Maximizing Exergy in Automotive Engines, in SAE 2007-01-0257. 2007

[5] Ho Teng, G.R., Chris Cowland, Waste Heat Recovery of Heavy-Duty Diesel Engines by Organic Rankine Cycle Part I: Hybrid Energy System of Diesel and Rankine Engines, in SAE 2007-01-0537. 2007

[6] Yang, J., Develop Thermoelectric Technology for Automotive Waste Heat Recovery, in Deer conference. 2006.

[7] Iacopo Vaja, A.G., Internal Combustion Engine (ICE) bottoming with Organic Rankine Cycles (ORCs) Energy, 2010. 35: p. 1084-1093.